

Probing the cosmic acceleration from combinations of different data sets

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Abstract

We examine in some detail the influence of the systematics in different data sets including type Ia supernova sample, baryon acoustic oscillation data and the cosmic microwave background information on the fitting results of the Chevallier-Polarski-Linder parametrization. We find that the systematics in the data sets does influence the fitting results and leads to different evolutionary behavior of dark energy. To check the versatility of Chevallier-Polarski-Linder parametrization, we also perform the analysis on the Wetterich parametrization of dark energy. The results show that both the parametrization of dark energy and the systematics in data sets influence the evolutionary behavior of dark energy.

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I. INTRODUCTION

The convincing fact that our universe is experiencing accelerated expansion [1, 2] has become one of the most important and mysterious issues of modern cosmology. In the framework of general relativity, the cosmic acceleration is attributed to an exotic energy called dark energy (DE). The simplest candidate of the DE is the cosmological constant with equation of state (EOS) $w = -1$. Despite some severe problems such as the cosmological constant problem and the coincidence problem, the cosmological constant is favored by current astronomical observations. Besides, there are some other DE models with EOS varying with cosmic time either above -1 or below -1 . Interestingly, some current observations even give the hint that EOS of DE has crossed -1 at least once [3, 4]. To narrow down the DE candidates, one has to examine the EOS carefully by confronting different observational data sets including the type Ia supernova (SNIa) luminosity distance, the cosmic microwave background (CMB) temperature anisotropy and the baryon acoustic oscillations (BAO) in the galaxy power spectrum, and this could be the best what we can do to approach the truth of DE.

In addition to the EOS, a new diagnostic of DE was introduced in [5] which is called Om diagnostic. It is a combination of the Hubble parameter and the cosmological redshift, which depends upon the first derivative of the luminosity distance and is less sensitive to observational errors than the EOS. If the value of Om is the same at different redshifts, then the DE is the cosmological constant. The slope of Om can differentiate between different DE models with $w > -1$ or $w < -1$ even if the value of the matter density is not accurately known.

Analyzing the Constitution SNIa sample [6] together with the BAO data [7, 8] by using the popular Chevallier-Polarski-Linder (CPL) parametrization [9, 10], it was revealed that there appears the increase of Om and w at redshifts $z < 0.3$ [11]. This suggests that the cosmic acceleration may have already been over the peak and now the acceleration is slowing down. However, including the CMB shift parameter which is another independent observable at high redshift, it was found that the result changes dramatically and the value of Om becomes un-evolving which is consistent with the Λ CDM model. Further check shows that the CPL ansatz is unable to fit the data simultaneously at low and high redshifts. It was argued that this could either due to the systematics in some of the data sets which is not

sufficiently understood or because the CPL parametrization is not versatile to accommodate the cosmological evolution of DE suggested by the data [11]. The data sets used in the analysis of [11] are limited to the Constitution set of 397 SNIa in combination with BAO distance ratio of the distance measurements obtained at $z = 0.2$ and $z = 0.35$ and the CMB shift parameter. It is expected that if more combinations of new data sets are included, these arguments can be clarified. In [4], it was showed that the result of the analysis on the CPL model [11] heavily depends on the choice of BAO data. The result obtained by using the BAO distance ratio data was found not consistent with that by using other observational data, and this inconsistency can be overcome if the BAO A parameter [12] is employed instead [4]. In this work we are going to investigate this problem further by comparing different data set combinations among SNIa, BAO and CMB.

II. OBSERVATIONAL DATA

For the SNIa data, we use the Constitution sample [6] and the first year Sloan digital sky survey-II (SDSS-II) SNIa (hereafter Sdss2) [13]. The Constitution sample consists of the Union sample [14] together with 185 CfA3 SNIa data, which totally contains 397 SNIa. The CfA3 addition makes the cosmologically useful sample of nearby SNIa much larger than before, which reduces the statistical uncertainty to the point where systematics plays the largest role. To test the systematic differences and consistencies, in [6] four light curve fitters, *SALT*, *SALT2*, *MLCS2k2* with $R_V = 3.1$ (MLCS31), *MLCS2k2* with $R_V = 1.7$ (MLCS17), have been used. For the Constitution SNIa data using the template *SALT* (hereafter Csta), the intrinsic uncertainty of 0.138 mag for each CfA3 SNIa, the peculiar velocity uncertainty of 400km/s, and the redshift uncertainty have been considered [6]. These data were suggested by observers to be the best data for model independent analysis of the expansion history. The Constitution SNIa data using the template *SALT2* (hereafter Cstb), excludes the SNIa with $z < 0.01$ or $t_{1st} > 10d$, so it has 351 SNIa data. Using the template *MLCS17* on the Constitution data (hereafter Cstc), the SNIa with $A_v \geq 1.5$ and $t_{1st} > 10d$ has been cut out and it excludes those SNIa whose *MLCS17* fit has a reduced χ^2_ν being 1.6 or higher, thus Cstc has only 372 SNIa data. The Cstd sample is formed by using the template *MLCS31* on the Constitution sample and cutting out the SNIa with $A_v \geq 1.5$ and $t_{1st} > 10d$. It excludes any SNIa whose *MLCS31* fit has a reduced χ^2_ν

being 1.5 or higher, so that it contains 366 SNIa data. We will examine the systematic differences brought by the Constitution sample with different light curve fitters. In addition we will also consider Sdss2 sample and investigate the systematic difference it brought, to compare with the Constitution sample. The Sdss2 consists of 103 new SNIa with redshifts $0.04 < z < 0.42$, discovered during the first season of the SDSS-II supernova survey, 33 nearby SNIa with redshifts $0.02 < z < 0.1$, 56 SNIa with redshifts $0.16 < z < 0.69$ from ESSENCE [15, 16], 62 with redshifts $0.25 < z < 1.01$ SNIa from SNLS [17], and 34 SNIa with redshifts $0.21 < z < 1.55$ from HST. For simplicity, we only use the Sdss2 data with the template MLCS2K2. For the 288 Sdss2 SNIa data, we also consider the redshift uncertainties from spectroscopic measurements and from peculiar motions of the host galaxy. For the redshift uncertainty, $\sigma_{z,pec}$, arises from peculiar velocities of and within host galaxies, we take $\sigma_{z,pec} = 0.0012$. In addition, the intrinsic error of 0.16 mag is added to the uncertainty of the distance modulus [13].

To fit the SNIa data, we define

$$\chi^2(\mathbf{p}, H_0) = \sum_{i=1} \frac{[\mu_{obs}(z_i) - \mu(z_i, \mathbf{p}, H_0)]^2}{\sigma_i^2}, \quad (1)$$

where the extinction-corrected distance modulus $\mu(z, \mathbf{p}, H_0) = 5 \log_{10}[d_L(z)/\text{Mpc}] + 25$, σ_i is the total uncertainty in the SNIa data, and the luminosity distance for a flat universe is

$$d_L(z, \mathbf{p}, H_0) = \frac{1+z}{H_0} \int_0^z \frac{dx}{E(x)}, \quad (2)$$

where the dimensionless Hubble parameter $E(z) = H(z)/H_0$. Because the normalization of the luminosity distance is unknown, the nuisance parameter H_0 in the SNIa data is not the observed Hubble constant. We marginalize over the nuisance parameter H_0 with a flat prior, which leads to [18]

$$\chi_{sn}^2(\mathbf{p}) = \sum_{i=1} \frac{\alpha_i^2}{\sigma_i^2} - \frac{(\sum_i \alpha_i / \sigma_i^2 - \ln 10/5)^2}{\sum_i 1/\sigma_i^2} - 2 \ln \left(\frac{\ln 10}{5} \sqrt{\frac{2\pi}{\sum_i 1/\sigma_i^2}} \right), \quad (3)$$

where $\alpha_i = \mu_{obs}(z_i) - 25 - 5 \log_{10}[H_0 d_L(z_i)]$.

Besides considering these SNIa data sets individually, our analysis will also investigate the combination of SNIa data with the BAO data. For the BAO data, we first use the BAO distance measurements obtained at $z = 0.2$ and $z = 0.35$ from joint analysis of the 2dFGRS and SDSS data [8]. Defining $d_z(\mathbf{p}, H_0) = r_s(z_d)/D_V(z)$, where the comoving sound horizon

and effective distance are

$$r_s(z, \mathbf{p}) = \int_z^\infty \frac{dx}{c_s(x)E(x)}, \quad (4)$$

$$D_V(z, \mathbf{p}, H_0) = \left[\frac{d_L^2(z)}{(1+z)^2} \frac{z}{H(z)} \right]^{1/3} = H_0^{-1} \left[\frac{z}{E(z)} \left(\int_0^z \frac{dx}{E(x)} \right)^2 \right]^{1/3}. \quad (5)$$

The redshift z_d at the baryon drag epoch is fitted with the formula [19]

$$z_d = \frac{1291(\Omega_{m0}h^2)^{0.251}}{1 + 0.659(\Omega_{m0}h^2)^{0.828}} [1 + b_1(\Omega_b h^2)^{b_2}], \quad (6)$$

$$b_1 = 0.313(\Omega_{m0}h^2)^{-0.419} [1 + 0.607(\Omega_{m0}h^2)^{0.674}], \quad b_2 = 0.238(\Omega_{m0}h^2)^{0.223}, \quad (7)$$

where Ω_{m0} is the current value of the dimensionless matter energy density, Ω_b is the dimensionless baryon matter energy density, and $h = H_0/100$. The sound speed $c_s(z) = 1/\sqrt{3[1 + \bar{R}_b/(1+z)]}$, where $\bar{R}_b = 315000\Omega_b h^2 (T_{cmb}/2.7\text{K})^{-4}$ and $T_{cmb} = 2.726\text{K}$. In [8], two points $d_{0.2}$ and $d_{0.35}$ and their covariance matrix are given. We will use $d_{0.2} = 0.1905 \pm 0.0061$, $d_{0.35} = 0.1097 \pm 0.0036$ and their covariance matrix (hereafter Bao2) as the second sample of BAO data in the data fitting. When we use these data, we add two more parameters $\Omega_b h^2$ and h . Based on these two BAO distance measurements, we can derive the BAO distance ratio $D_V(0.35)/D_V(0.2) = 1.736 \pm 0.065$ (hereafter BaoR), which is relatively model independent quantity. This BAO distance ratio was employed in the analysis in [11]. In our case we will further use another two radial BAO data at redshifts $z = 0.24$ and $z = 0.43$ [20] by using $\Delta z(z) = H(z)r_s(z_d)/c$ (hereafter BaoZ). Combining BAO data sets Bao2 and BaoZ, we have the data set called Bao4. Therefore, for different BAO data sets, we can perform χ^2 statistics for the model parameter \mathbf{p} as follows

$$\chi_{BaoR}^2(\mathbf{p}) = \frac{[D_V(0.35)/D_V(0.2) - 1.736]^2}{0.065^2}, \quad (8)$$

$$\chi_{BaoZ}^2(\mathbf{p}, h, \Omega_b h^2) = \frac{[\Delta z(0.24) - 0.0407]^2}{0.0011^2} + \frac{[\Delta z(0.43) - 0.0442]^2}{0.0015^2}, \quad (9)$$

and

$$\chi_{Bao2}^2(\mathbf{p}, h, \Omega_b h^2) = \sum_{ij} \Delta d_i \text{Cov}^{-1}(d_i, d_j) \Delta d_j, \quad (10)$$

where $i, j = 0.2, 0.35$, $\Delta d_{0.2} = d_{0.2} - 0.1905$, $\Delta d_{0.35} = d_{0.35} - 0.1097$.

Since the SNIa and BAO data contain information about the universe at relatively low redshifts, we will include the CMB information by implementing the Wilkinson microwave anisotropy probe 5 year (WMAP5) data to probe the entire expansion history up to the last

scattering surface. In addition to employing the CMB shift parameter R by defining the reduced distance in the flat universe to the last scattering surface z_* as done in [11]

$$R(\mathbf{p}) = \sqrt{\Omega_{m0}} \int_0^{z_*} \frac{dz}{E(z)} = 1.71 \pm 0.019, \quad (11)$$

we will add the acoustic scale l_a in the data analysis. The acoustic scale l_a is defined by

$$l_a = \frac{\pi d_L(z_*)}{(1+z_*)r_s(z_*)} = 302.1 \pm 0.86, \quad (12)$$

where the redshift z_* is given by [21]

$$z_* = 1048[1 + 0.00124(\Omega_b h^2)^{-0.738}][1 + g_1(\Omega_{m0} h^2)^{g_2}] = 1090.04 \pm 0.93, \quad (13)$$

$$g_1 = \frac{0.0783(\Omega_b h^2)^{-0.238}}{1 + 39.5(\Omega_b h^2)^{0.763}}, \quad g_2 = \frac{0.560}{1 + 21.1(\Omega_b h^2)^{1.81}}. \quad (14)$$

We have three fitting parameters $x_i = (R, l_a, z_*)$ to include the CMB information now. Thus we have $\chi_{cmb}^2(\mathbf{p}, h, \Omega_b h^2) = \sum_{ij} \Delta x_i \text{Cov}^{-1}(x_i, x_j) \Delta x_j$, $\Delta x_i = x_i - x_i^{obs}$ and $\text{Cov}(x_i, x_j)$ is the covariance matrix for the three parameters [22]. The CMB information provides a systematic check of the DE model by combining with the low redshift SNIa and BAO data sets.

III. FITTING RESULTS

We employ the Monte-Carlo Markov Chain (MCMC) method to explore the parameter space \mathbf{p} and the nuisance parameters h and $\Omega_b h^2$ in the data analysis. Our MCMC code [18] is based on the publicly available package COSMOMC [23].

We first explore the widely used CPL parametrization [9, 10]

$$w(z) = w_0 + \frac{w_a z}{1+z}. \quad (15)$$

In this model, the dimensionless Hubble parameter for a flat universe is

$$E^2(z) = \frac{H^2(z)}{H_0^2} = \Omega_{m0}(1+z)^3 + (1 - \Omega_{m0})(1+z)^{3(1+w_0+w_a)} \exp(-3w_a z/(1+z)). \quad (16)$$

In this model, we have three parameters $\mathbf{p} = (\Omega_{m0}, w_0, w_a)$. Knowing the expansion history of the universe, we can construct the Om diagnostic by defining

$$Om(z) = \frac{E^2(z) - 1}{(1+z)^3 - 1}. \quad (17)$$

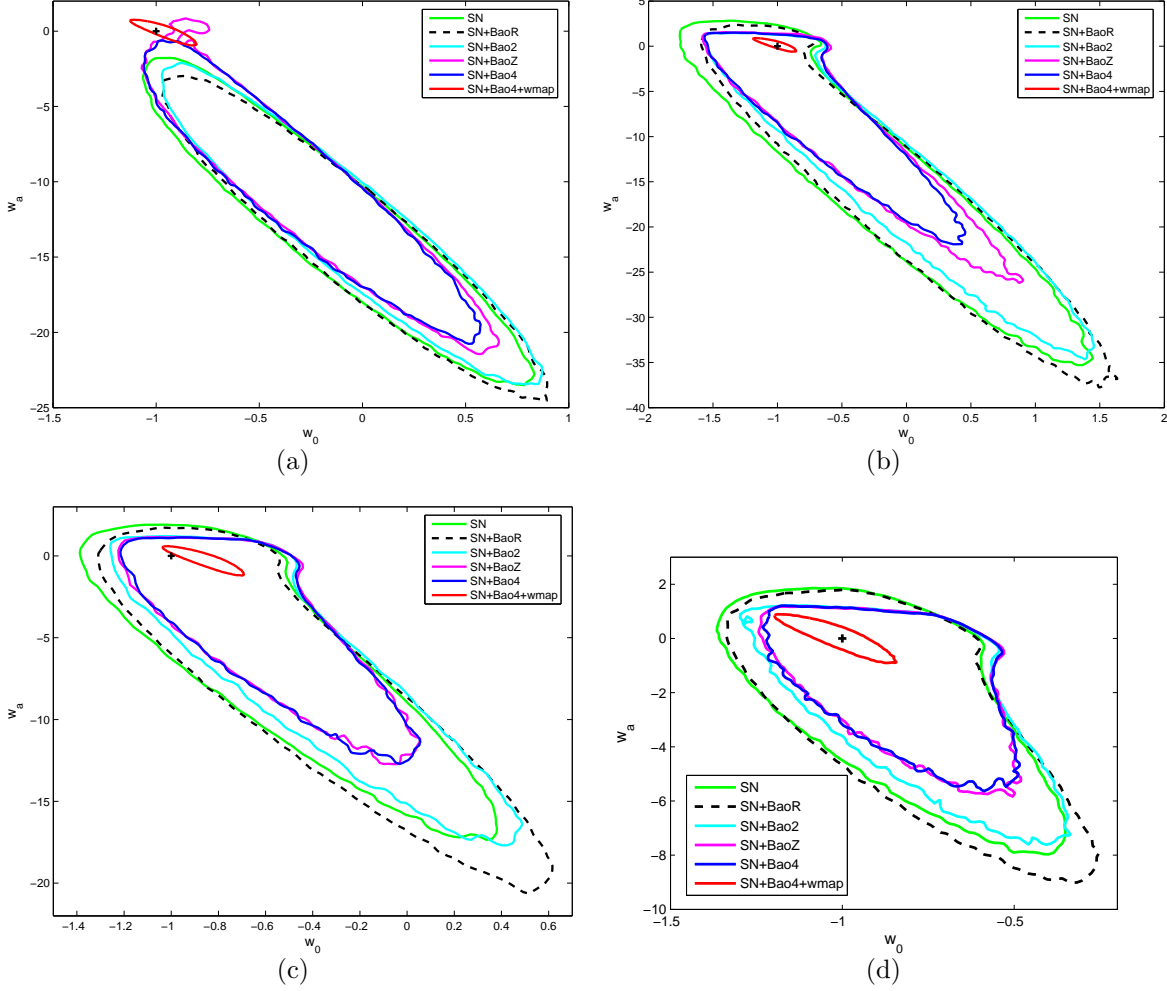


FIG. 1: The marginalized 1σ contours of w_0 and w_a in the CPL model. The green line is for SNIa, the dashed black line is for SNIa+BaoR, the cyan line is for SNIa+Bao2, the magenta line is for SNIa+BaoZ, the blue line is for SNIa+Bao4, and the red line is for SNIa+Bao4+WMAP5. The SNIa used in (a)-(d) are Csta, Cstb, Cstc, and Cstd, respectively.

Om diagnostic is useful in establishing the properties of DE at low redshifts. The constant Om indicates that the DE is the cosmological constant and the bigger value of Om shows that w is bigger [5]. $Om(z)$ is less sensitive to observational errors than EOS $w(z)$. Due to the degeneracy between Ω_{m0} and w , the property of $w(z)$ depends on the current value of matter energy density Ω_{m0} . However, Om diagnostic provides a null test of the cosmological constant without knowing the exact value of Ω_{m0} . To reconstruct $Om(z)$, we need to apply the specific model and model parameters. Following [11], we consider the uncertainties of Ω_{m0} , w_0 and w_a when we reconstruct $Om(z)$.

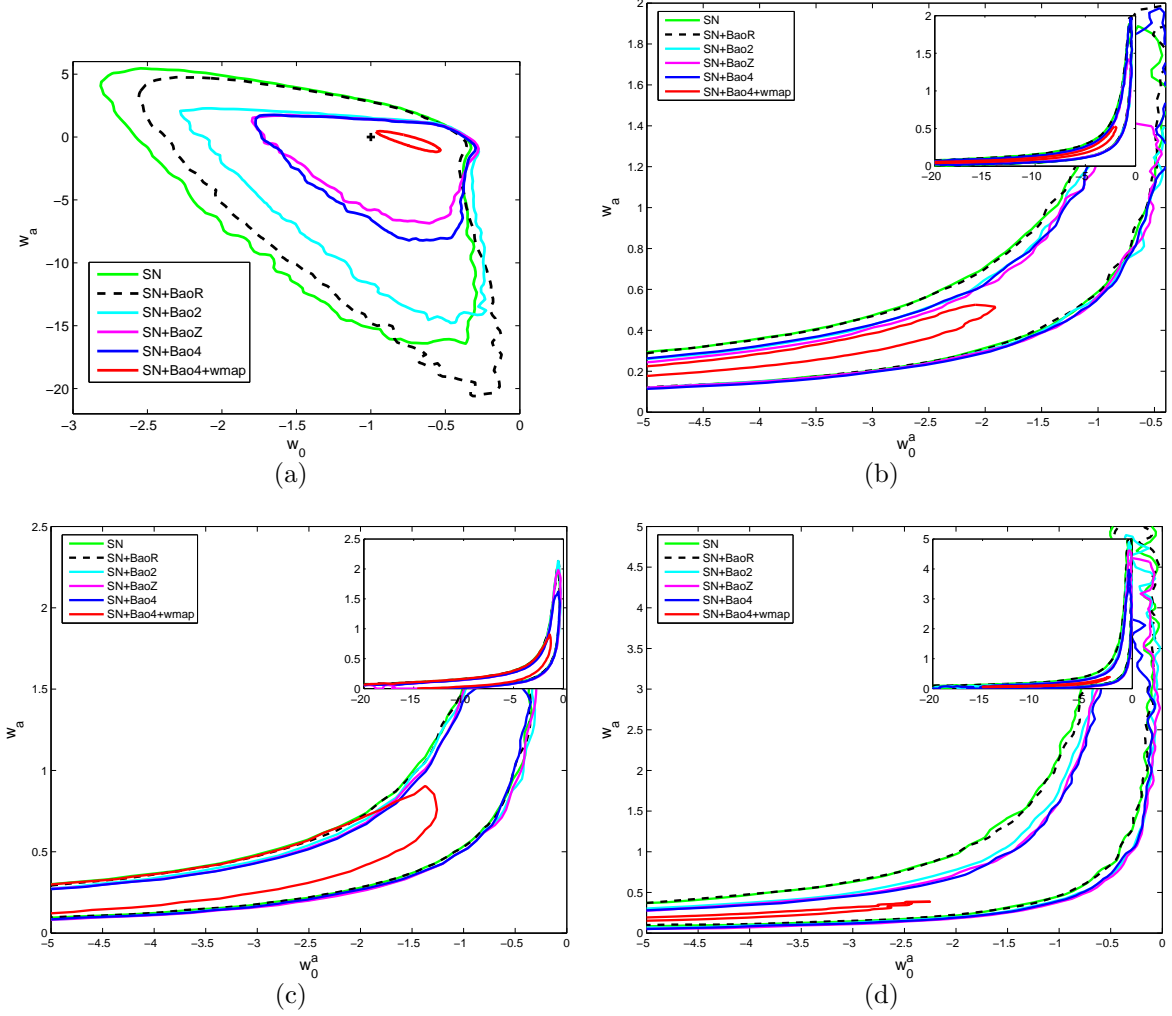


FIG. 2: The marginalized 1σ contours of w_0 (w_0^a) and w_a . The label of contours is the same as Fig. 1. (a) is for the CPL model with Sdss2 SNIa data. (b)-(d) are for the Wetterich model. The SNIa used in (b)-(d) are Csta, Cstd and Sdss2, respectively.

Fig. 1 shows contours of the fitting results for the CPL parametrization by combining different SNIa data together with different BAO data and the combination of the WMAP5 data. The SNIa data used in Figs. 1a-1d and 2a are Csta, Cstb, Cstc, Cstd, and Sdss2, respectively. The green lines are for using just SNIa data alone with different templates. The dashed black lines are for SN+BaoR, the cyan lines are for SN+Bao2. Since the BaoR data is derived from Bao2 data, so the result using BaoR data is compatible with that of Bao2. Also we can see that the constraint is a little better with Bao2 than that with BaoR. The magenta lines are for SN+BaoZ, we see that the constraint from BaoZ is in general consistent with that from Bao2 although the former gives a little tighter constraint. These behaviors keep

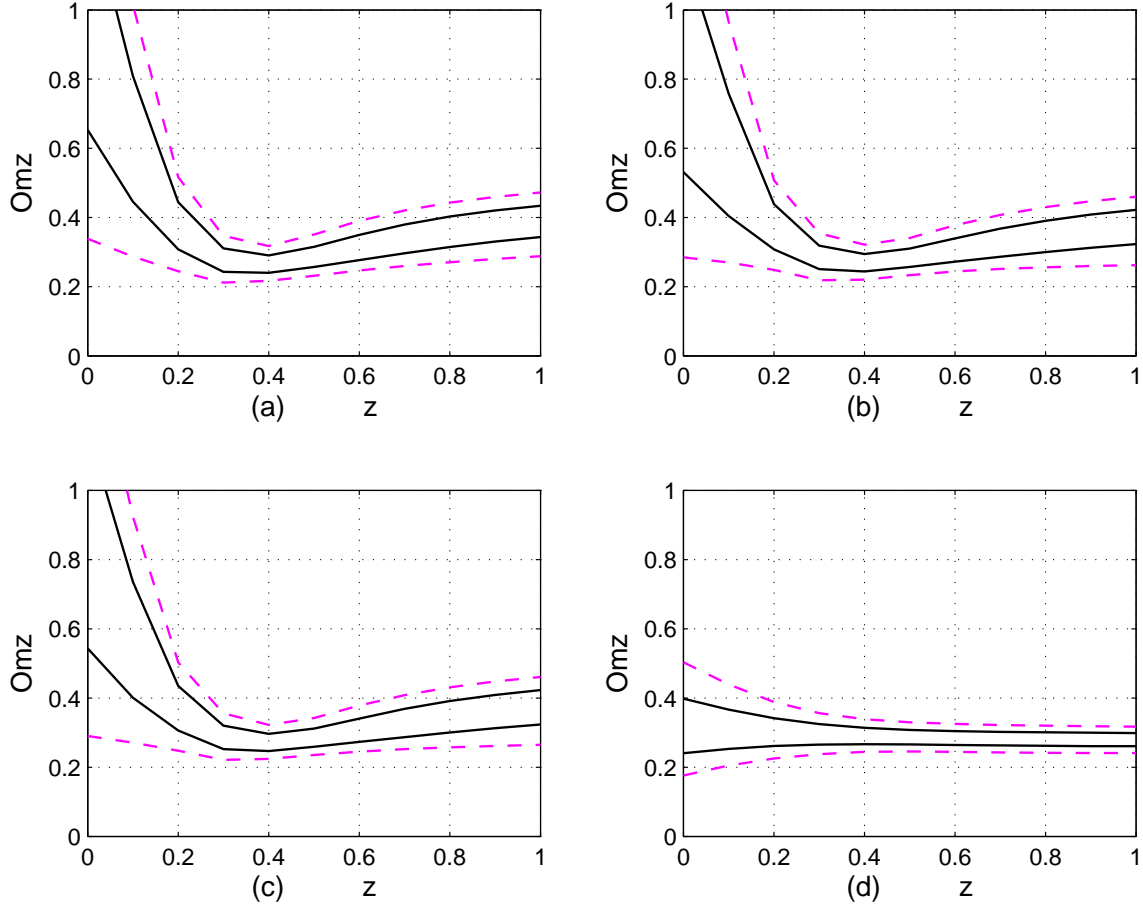


FIG. 3: The marginalized 1σ and 2σ errors of $Om(z)$ reconstructed in the CPL model by using the Csta SNIa data. (a) uses the combination of SNIa+BaoR, (b) uses the combination of SNIa+BaoZ, (c) uses the combination of SNIa+Bao4 and (d) uses the combination of SNIa+Bao4+WMAP5.

the same for SNIa data with different templates. The blue lines are for SN+Bao4, where Bao4 is the combination of Bao2+BaoZ. The combination of the SN+Bao4+WMAP5 is shown in the red solid lines. The observation that the CPL ansatz is strained to describe the DE behavior suggested by data at low and high redshifts by comparing Csta+BaoR and Csta+BaoR+CMB shift parameter [11] has been reduced by using the same SN data (Csta) with BaoZ or Bao4, or other SN data sets (Cstb-Cstd, Sdss2) with arbitrary combinations of BAO data. This confirms that the systematics in some of the data sets really matters the fitting results.

For the Csta data, the reconstructed $Om(z)$ for SNIa data in combination with BAO and CMB data is shown in Fig. 3. Since $Om(z)$ is not a constant at 1σ level if we combine

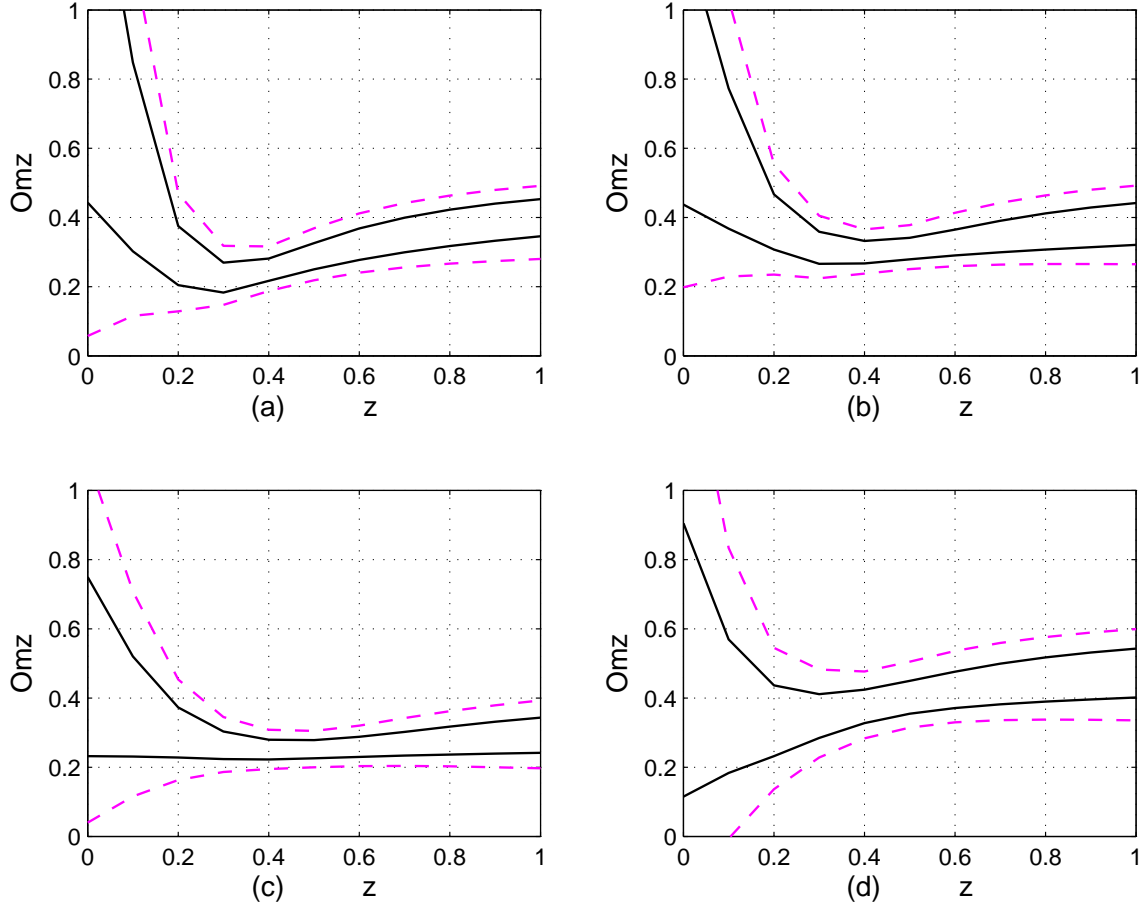


FIG. 4: The marginalized 1σ and 2σ errors of $Om(z)$ reconstructed in the CPL model with SNIa+BaoR. The SNIa data used in (a)-(d) are Cstb, Cstc, Cstd, and Sdss2, respectively.

Cata SNIa with BaoR, BaoZ or Bao4, so the Λ CDM model is excluded at 1σ level if use the combination of Csta SNIa and BAO data. However, when the WMAP5 data is added, the Λ CDM model is consistent at 1σ level. The growth in the value of $Om(z)$ at low redshifts becomes smaller when we change the BAO data from BaoR to BaoZ or Bao4. In Fig. 4, we show the marginalized 1σ and 2σ errors of $Om(z)$ reconstructed using the BaoR and different SNIa data sets. The growth in the value of $Om(z)$ at low redshifts in Fig. 3a by using Csta+BaoR as observed in [11] gets flattened if we change SNIa data sets from Csta to Cstb, Cstc, Cstd and Sdss2. This shows that the finding in [11] is not a general behavior even at low z . The evolutionary behavior of $Om(z)$ at low redshifts is changed for different selections of the SNIa data. Thus the striking observation that our universe is slowing down [11] based on the fitting at low redshifts for CPL ansatz is caused by the systematics of the specially chosen SNIa and BAO data sets. By choosing some other data sets, the CPL

parametrization is in compatible with combinations of data sets at low and high redshifts. The un-evolving $Om(z)$ is also allowed even at low redshifts. From Figs. 3a and 4, we see that the Λ CDM model is not allowed at 1σ level for the combination of BaoR and Csta, Cstb or Cstc, although the cosmological constant is inside the 1σ contours of w_0 and w_a in Figs. 1b and 1c. This shows the advantage of Om diagnostic because the uncertainty of Ω_{m0} is taken accounted for.

In the above discussions we have focused on the commonly used functional form for DE, the CPL parametrization, and argued that the systematics in SNIa and BAO data sets really affects the evolution of the DE and the acceleration of the universe. Besides the systematics of data sets, whether the influences on the evolution of the DE and the acceleration are caused by the specific choice of the parametrization of the DE is another interesting question to ask. In [11], the incompatibility of the CPL ansatz fitting to the data simultaneously at low and high redshifts was attributed to the versatility of the CPL parametrization. Choosing another ansatz of DE parametrization, it was found significantly better than that of CPL, that ansatz can provide a good fit to the combination of Csta+BaoR and the CMB shift data. In the rest of this work we are going to further examine the versatility of the CPL parametrization by considering a different ansatz of DE parametrization and confronting it with different combinations of various data sets as used above.

What we are going to study is the Wetterich parametrization of the form [24]

$$w(z) = \frac{w_0}{1 + w_a \ln(1 + z)}. \quad (18)$$

When $z = 0$, $w(z) = w_0$, and at large redshift $z \gg 1$, $w(z) \approx 0$. The Wetterich parametrization becomes the constant parametrization $w(z) = w_0$ when $w_a = 0$.

In this model, the dimensionless Hubble parameter for a flat universe is

$$E^2(z) = \Omega_{m0}(1 + z)^3 + (1 - \Omega_{m0})(1 + z)^3[1 + w_a \ln(1 + z)]^{3w_0/w_a}. \quad (19)$$

To ensure the positivity of DE, we require that $w_a \geq 0$. For the convenience of numerical calculation, we take the independent parameters as $w_0^a = w_0/w_a$ and w_a . The parameters in this model are $\mathbf{p} = (\Omega_{m0}, w_0^a, w_a)$, the number is the same as those in the case of CPL ansatz.

The compatibility checks in confronting with different SNIa, BAO data sets together with CMB data are shown in Figs. 2b-2d. In Figs. 2b-2d, we have used the Csta, Cstd and Sdss2

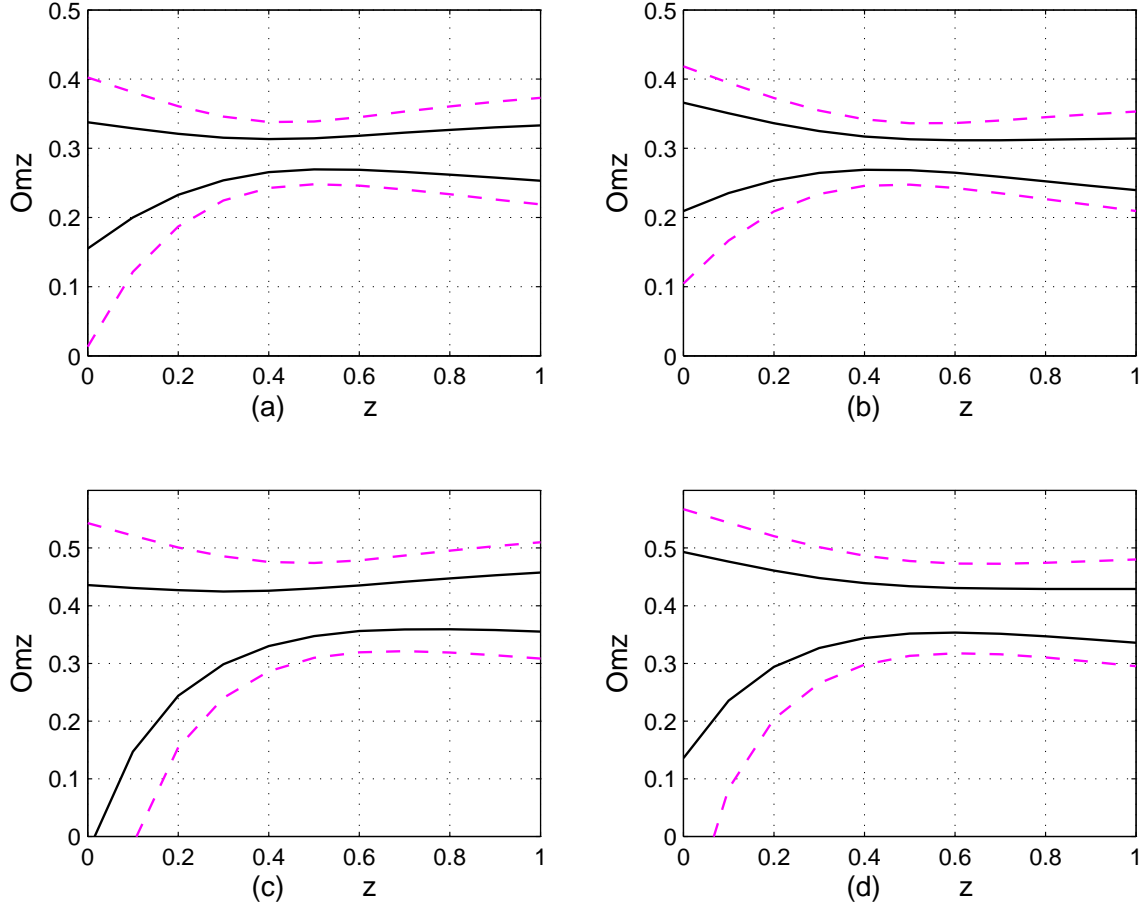


FIG. 5: The marginalized 1σ and 2σ errors of $Om(z)$ reconstructed in the Wetterich model. (a) uses the combination of Csta SNIa+BaoR, (b) uses the combination of Csta SNIa+BaoZ, (c) uses the combination of Sdss2 SNIa+BaoR, and (d) uses the combination of Sdss2 SNIa+BaoZ.

SNIa data sets, respectively. As indicated in Fig. 1 and Fig. 2, the green lines are just for SNIa data alone, the dashed black lines are for SN+BaoR, the cyan lines are results for SNIa+Bao2, the magenta lines indicate SNIa+BaoZ, the blue lines are for SNIa+Bao4, and the solid red lines are for the combination of SNIa+Bao4+WMAP5. It is interesting to see that different from the CPL ansatz, this parametrization allows the compatibility of different SNIa, Bao and CMB data sets, even for comparing the combinations of Csta+BaoR, Csta+BaoZ and Csta+Bao4+WMAP5. The Wetterich ansatz is found able to fit different data sets both at low and high redshifts. In Fig. 5, we present the behaviors of the $Om(z)$ reconstructed by comparing the influence of different SNIa and BAO data sets. Interestingly, the evolution of $Om(z)$ is not affected much by different SNIa and BAO data sets. The

$Om(z)$ is perfectly consistent with Λ CDM for different data sets.

For the comparison of different data sets and different parametrizations, we summarize the minimum value of χ^2 in Table I. From Table I, we observe the reliability of parametrizations when using different data sets. Comparing two different parametrizations, we see that both of them can fit well of the data, while the CPL model is a little better than the Wetterich parametrization for the Csta SNIa and the combination of Csta SNIa with BAO data.

TABLE I: The minimum value of χ^2 for different combinations of data sets and models.

Data	CPL (χ^2/DOF)	Wetterich
Csta	462.06/394	466.33/394
Csta+BaoR	462.43/395	467.62/395
Csta+Bao2	462.45/394	467.73/394
Csta+BaoZ	462.10/394	466.60/394
Csta+Bao4	464.11/396	468.57/396
Csta+Bao4+WMAP5	468.73/399	468.69/399
Sdss2	227.55/285	227.09/285
Sdss2+BaoR	229.77/286	229.45/286
Sdss2+Bao2	229.93/285	229.65/285
Sdss2+BaoZ	228.77/285	228.57/285
Sdss2+Bao4	231.15/287	231.02/287
Sdss2+Bao4+WMAP5	231.71/290	231.94/290

IV. CONCLUSION

To summarize, we have examined the influence of the systematics in different data sets in SNIa and BAO on the fitting results of the CPL parametrization. We found that the tension observed in [11] between low z (Csta+BaoR) and the high z (CMB) data is not a general behavior. By using SNIa with other templates and other BAO data sets, the incompatibility of the CPL parametrization will disappear. This result supports the speculation that the systematics in the data sets can affect the fitting results and leads to different evolution of the DE model [11]. However this answer is still not definite. The different evolutions in $Om(z)$

as we observed by using different combinations of various SNIa and BAO data sets disappear when we use the Wetterich parametrization to replace the CPL parametrization. This again brings the problem as raised in [11] that the CPL parametrization might be blamed to be not so versatile. In order to disclose the exact answer, we have to examine more models of DE. This work offers the attempt of using different combinations of various data sets at low and high redshifts to examine the effects of data systematics on the evolution of the DE and the acceleration of the universe. Further investigation along this line by including more data sets and examining more DE models are called for and we will report our progress in this direction in the future work.

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